PATENT APPLICATION OF

EVREN ERYUREK and KADIR KAVAKLIOGLU

ENTITLED

ROOT CAUSE DIAGNOSTICS

Docket No. P32.12-0019

ROOT CAUSE DIAGNOSTICS

The present application is a Continuation-In-Part of and claims priority of U.S. patent application Serial No. 09/303,869, filed May 3, 1999,

5 which is a Divisional of application Serial No. 08/623,569, filed March 28, 1996, now U.S. Patent No. 6,017,143 the contents of which are hereby incorporated by reference in their entirety.

BACKGROUND OF THE INVENTION

10 The present invention relates to industrial process controls and process control loops. More specifically, the invention relates to diagnostics of such loops.

Process control loops are used in process

15 industries to control operation of a process, such as an oil refinery. A transmitter is typically part of the loop and is located in the field to measure and transmit a process variable such as pressure, flow or temperature, for example, to control room equipment.

20 A controller such as a valve controller is also part of the process control loop and controls position of a valve based upon a control signal received over the control loop or generated internally. Other controllers control electric motors or solenoids for

25 example. The control room equipment is also part of the process control loop such that an operator or computer in the control room is capable of monitoring the process based upon process variables received from transmitters in the field and responsively

controlling the process by sending control signals to the appropriate control devices. Another process device which may be part of a control loop is a portable communicator which is capable of monitoring and transmitting process signals on the process control loop. Typically, these are used to configure devices which form the loop.

Various techniques have been used to monitor operation of process control loops and to diagnose and identify failures in the loop. However, it would also be desirable to identify the source or "root cause" of a failure, such as by identifying a particular device or component in the system which is the source of an aberration in process operation. This would provide additional information to an operator as to which device in the process needs repair or replacement.

SUMMARY OF THE INVENTION

In various aspects, an industrial process diagnostic apparatus is provided which can identify a source, or "root cause", of an aberration in an industrial process. In one aspect, the apparatus includes a plurality of process configuration models and each model is related to a physical (or actual) implementation of an industrial process. One of the plurality of models can be selected and diagnostics performed using the selected model and at least one process signal related to the process. Based upon the

diagnostics, a root cause of the aberration is determined.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a simplified diagram showing a process control loop including a transmitter, controller, hand-held communicator and control room.

Figure 2 is a schematic diagram of a process control loop model for a liquid level loop.

Figure 3 is a schematic diagram of a process control loop model for a flow rate control loop.

Figure 4 is a block diagram of a device for implementing one example of the present invention.

Figure 5 is a block diagram showing one example hardware implementation of Figure 4.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention can be used with industrial processes to identify the "root cause" of an aberration which occurs in the process. Figure 1 is a diagram showing an example of an industrial process control system 2 used to control flow of process fluid system 2 includes process piping 4 which carries a process fluid and two wire process control loop 6 carrying loop current I. A transmitter 8, controller 10, which couples to a final control element in the loop such as an actuator, valve, a pump, motor or solenoid, communicator 12, and control room 14 are all part of process control system 2. If an aberration occurs in the operation of the process, the present invention

can be used to identify the cause of the observed aberration.

Loop 6 is shown in one configuration for illustration purposes and any appropriate process control loop may be used such as a 4-20 mA loop, 2, 3 or 4 wire loop, multi-drop loop and a loop operating in accordance with the HART®, Fieldbus or other digital or analog communication protocol. In operation, transmitter 8 senses a process variable such as flow using sensor 16 and transmits the sensed process variable over loop 6. The process variable may be received by controller/valve actuator 10, communicator 12 and/or control room equipment 14. Controller 10 is shown coupled to valve 18 and is capable of controlling the process by adjusting valve 18 thereby changing the flow in pipe 4. Controller 10 receives a control input over loop 6 from, for example, control room 14, transmitter 8 or communicator 12 and responsively adjusts valve 18. In another embodiment, controller 10 internally generates the control signal based upon process signals received over loop 6. Communicator 12 may be the portable communicator shown in Figure 1 or may be a permanently mounted process unit which monitors the process and performs computations. Process devices include, for example, transmitter 8 (such as a 3095 transmitter available from Rosemount Inc.), controller 10, communicator 12 and control room 14 shown in Figure 1. Another type of process device is

a PC, programmable logic unit (PLC) or other computer coupled to the loop using appropriate I/O circuitry to allow monitoring, managing, and/or transmitting on the loop.

5   Figure 2 is a simplified diagram 50 of a graphical model of a process control loop 50 for controlling the level of liquid in a tank 52. As discussed below, such models can be selected and used to diagnose a root cause of an aberration in process

10 operation. A level transmitter 54 measures the level of liquid in tank 52 and provides a primary process variable (PV) to a controller 56. Controller 56 as illustrated is a PID controller, however, it can be any type of controller. Controller 56 also receives a

15 setpoint (SP) which is related to a desired level for the liquid within tank 52. Using a known control algorithms, controller 56 provides a control demand (CD) output to a valve 58. An optional valve position sensor 60 can be used to measure the actual position

20 of the valve stem of valve 58. Other optional components for this particular example model include a pump 62 configured to draw liquid from tank 52, a transmitter 64 configured to measure the inlet flow rate and a transmitter 66 configured to measure the

25 outlet flow rate. As described below, the models and optional components for a model are stored in a memory and can be selected by an operator or other selection technique. In various aspects, the memory can be located or accessible to any device which

couples to the process or has access to process signals.

It is preferable to perform the diagnostics of the present invention on the process control system after the operation of the process has settled and is in a steady state mode. This is ensured by observing the mean and standard deviation of process signals. The mean (μ) and standard deviation (Σ) of each of the process signals (such as process variables and control signals) are evaluated for a set of N measurements, the mean and standard deviation can be evaluated as follows:

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad\qquad \text{EQ. 1}$$

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - \mu\right)^2} \qquad\qquad \text{EQ. 2}$$

The number of points, N, depends upon the duration and sampling rates of the signal. In Equations 1 and 2, X_i is the value of a process signal taken at sample number i. Initially, a sampling period of ten minutes can be used with a sampling rate of one sample per second. In one example, the loop is determined to be operating in a steady state mode if the process mean is 100 inH_2O (with 1 inH_2O standard deviation) and the subsequent process means are between 97 inH_2O and 103 inH_2O. One patent which is related to determination of process stability prior to initiating diagnostics in U.S. Patent No. 6,119,047, issued September 12, 2000,

which is incorporated herein by reference in its entirety.

Once steady state operation has been reached, it is also desirable to discard data transients or spikes. One technique to identify such data is by successively comparing the signal mean with the signal standard deviation. The difference in the mean between two successive blocks of data (μ_1 and μ_2) should be less than the standard deviation divided by the square root of N, the number of samples. This can be expressed as:

$$\mu_1 - \frac{\sigma_1}{\sqrt{N}} \leq \mu_2 \leq \mu_1 + \frac{\sigma_1}{\sqrt{N}} \qquad \text{EQ. 3}$$

where μ is the mean of the previous block, μ_2 is the mean of the current block, N is the number of points in a block, and σ_1 is the standard deviation of the previous block.

Depending on the process signals which are available for performing diagnostics and used with the model, different root causes can be identified. For example, in the case of the process model shown in Figure 2, there are three different cases:

Case	Available Signals	Monitored Faults
1	SP PV CD	Level Sensor Drift Valve Problem
2	SP PV CD VP	Level Sensor Drift Valve Problem
3	SP PV CD VP	Level Sensor Drift Valve Problem Liquid Leak

	IF	
	OF	

TABLE 1

During an initial training phase, all of the process signals are collected for a user selectable amount of time, for example, 20 minutes. The mean and

5 standard deviations of the signals are evaluated. This training phase is repeated until the process enters steady state. Once the process is in steady state, trained values (i.e., "nominal values") for the mean (μ_t) and standard deviation (σ_t) for each of

10 the process signals are stored.

Additionally, prior to identifying a root cause fault, individual process signals can be evaluated to ensure that the process is operating properly. For example, the primary process variable (PV) can be

15 evaluated. In the case of liquid level illustrated in Figure 2:

CONDITION	FAULT
PV>0.95*PV_RANGE	LEVEL HIGH (TANK OVERFLOW)
PV<0.05*PV_RANGE	LEVEL LOW (TANK DRY)

TABLE 2

Where PV_RANGE is the range (maximum and minimum) of

20 the level. This value can be stored in a memory accessible by the process control system when the process control system is configured or can be entered by a user. Similarly, for the control signal (CD), the following faults can be identified:

CONDITION	FAULT

CD<5%	CONTROL WOUND DOWN
CD>95%	CONTROL WOUND UP

TABLE 3

In the example of Table 3, it is assumed that the control demand is a percentage between 0 and 100. If available, a similar test can be performed on the valve position (VP) process signal.

During a monitoring phase, the various process signals are monitored to determine if they have undergone no change (NC), an upward deviation (U) (the mean signal is above the training mean), or a downward variation (D) (the mean signal is less than a training mean). An NC condition is determined if:

$$\mu_t - \frac{\sigma_t}{\sqrt{N}} \leq \mu \leq \mu_t + \frac{\sigma_t}{\sqrt{N}} \qquad \text{EQ. 4}$$

where μ_t is the mean of the training block, μ is the mean of the current block, N is the number of points in a block, and σ_t is the standard deviation of the training block, μ_t and Σ_t are the mean and standard deviation, respectively, of the process signal stored during the training phase. N is the number of samples and μ is the current mean of the process signal.

An upward variation (U) condition is identified if:

$$\mu > \mu_t + \frac{\sigma_t}{\sqrt{N}} \qquad \text{EQ. 5}$$

where μ_t is the mean of the training block, μ is the mean of the current block, N is the number of points

in a block, and σ_t is the standard deviation of the training block.

Finally, a downward variation (D) condition is identified if:

5
$$\mu < \mu_t - \frac{\sigma_t}{\sqrt{N}}$$
EQ. 6

where μ_t is the mean of the training block, μ is the mean of the current block, N is the number of points in a block, and σ_t is the standard deviation of the training block.

10   Depending upon the number of process signals which are available, a different root cause can be identified as the source of an aberration in the process. For example, if the setpoint, primary variable and control demand process signals are

15 available, a level sensor drift or valve related problem can be identified. An example rule base is given in Table 4:

| SIGNALS | FAULT |
	Level Sensor Drift or Valve Problem
SP	NC
PV	NC
CD	U or D

20   **TABLE 4**

If an additional process signal is available, the actual valve position (VP), then the root cause

can be more specifically identified as given in Table 5:

SIGNALS	FAULT	
	Level Sensor Drift	Valve Problem
SP	NC	NC
PV	NC	NC
CD	U or D	U or D
VP	U or D	NC

TABLE 5

5   Finally, if the inflow rate (IF) and outflow rate (OF) process signals are available, it is also possible to determine if there is a leak in tank 52 as shown in the rule base of Table 6:

SIGNALS	FAULT		
	Level Sensor Drift	Valve Problem	Liquid Leak
SP	NC	NC	NC
PV	NC	NC	NC
CD	U or D	U or D	D
VP	U or D	NC	D
IF	NC	NC	NC
OF	NC	NC	D

TABLE 6

If the changes in the process signals do not
match any of the rules set forth in Tables 4, 5 and
6, an unknown fault output can be provided. Further,
these rules apply if the process 50 includes pump 62
or operates based upon a pressure differential which
is used to drain tank 52.

Figure 3 is a simplified diagram 100 of a
graphical model of a process control loop to control
a flow rate. This illustrates another example process
control loop. In Figure 3, a tank 102 (or a pump 103
or other source of a differential pressure) can
provide a flow of process fluid. A transmitter 104
senses the flow rate and provides the primary process
variable (flow rate) to controller 106. Controller
106 also receives a setpoint (SP) and provides a
control demand (CD) signal to valve 108. Valve 108
may optionally report back the actual position of its

valve stem (VP). Additional options include a pressure transmitter 110 configured to sense a process pressure (PT) and a redundant flow transmitter 112 configured to sense a redundant flow

5   rate (FT2).

In operation, the mean and standard deviation are determined during a training phase in a manner similar to that described with respect to Figure 2 and as set forth in Equations 1 and 2, above.

10 However, because a flow rate control typically responds relatively fast, a shorter learning duration can be used, for example two minutes.

Depending upon the number of different process signals which are available, a number of different

15 root causes can be identified as illustrated in Table 7:

Case	Available Signals	Monitored Faults
1	SP PV CD	Flow Sensor Drift Valve Problem
2	SP PV CD VP	Flow Sensor Drift Valve Problem
3	SP PV CD VP FT2	Flow Sensor Drift Valve Problem Liquid Leak

TABLE 7

Prior to identifying a root cause, basic faults can be checked for. For example, using the rule base in Table 8:

CONDITION	FAULT
PT is D	HEAD LOSS

TABLE 8

Further, the condition of the valve can be determined as follows:

CONDITION	FAULT
CD<5%	CONTROL WOUND DOWN
CD>95%	CD WOUND UP

TABLE 9

Using additional process variables, a "root cause" of an aberration in the process can be identified. When the setpoint, primary process variable and control demand signals are available flow sensor drift or a valve problem can be identified as the root cause of the process aberration as follows:

SIGNALS	FAULT Flow Sensor Drift or Valve Problem
SP	NC
PV	NC
CD	U or D

TABLE 10

If an additional process signal is available, the actual valve position (VP), then the root cause can be identified as flow sensor drift or a valve problem as follows:

SIGNALS	FAULT	
	Flow Sensor Drift	Valve Problem
SP	NC	NC
PV	NC	NC
CD	U or D	U or D
VP	U or D	NC

TABLE 11

Finally, if a redundant transmitter is used to measure a second flow rate variable (FT2), then a leak in the process can also be identified:

SIGNALS	FAULT		
	Level Sensor Drift	Valve Problem	Liquid Leak
SP	NC	NC	NC
PV	NC	NC	NC
CD	U or D	U or D	D
VP	U or D	NC	D
FT2 SIGNALS	U or D	NC	D

TABLE 12

Figure 4 is a block diagram illustrating a process device 100 which implements one example embodiment of the present invention. Process device 100 includes a root cause analysis block 102 which

5   receives a control signal CD through a control signal input 104, a process variable PV through a process variable input 106 and a setpoint SP through a setpoint input 108. Additional process signals (PS_1, PS_2 . . .) can be received through other inputs such

10 as process signal input 110, 111, etc. depending on the number of additional process signals which are available.

The root cause analysis block 102 is also coupled to a plurality of process configuration

15 models 112. Models 112 can be stored, for example, in a system memory. In the embodiment illustrated, there are a total of X different models which correspond to possible process control configurations. In this example, each model includes a graphical model GM_1 . .

20 . GM_x which provide graphical illustrations of the process. This can be used to provide a graphical user interface to facilitate entry of configuration data by an operator. For example, a graphical model can be similar to the diagrams shown in Figures 2 and 3.

25 Each process model can receive any number of process signals (PS_{1A}, PS_{1B}, etc.). In the specific examples shown in Figures 2 and 3, there are a minimum of three process signals, the control demand CD, the primary process variable PV and the setpoint

SP which are required to identify the root cause of an aberration in the process. In one embodiment, the number of process signals associated with a model is the minimum number of process signals required to perform the root cause analysis, or a greater number of process signals, as desired.

Next, each model can contain any number of optional process signals (OP_{1A}, OP_{1B}, . . .). Each optional process signal corresponds to a process signal (PS_1, PS_2, . . .) received through inputs 110, 111, etc. In the example of Figure 2, the valve position VP, inflow rate IF and outflow rate OF are examples of such optional process signals. Some models can be configured which have no additional optional process signals.

Next, each model contains any number of rule bases (RB_{1A}, RB_{1B}, . . .) which are used to determine the root cause based upon the received process signals (the require minimum process signals PS_{1A}, PS_{1B}, . . . and any optional process signals OP_{1A}, OP_{1B} . . .). Examples of rule bases are shown in Tables 4, 5, 6, 10, 11 and 12 which were discussed above. Note that the present invention is not limited to the particular use of the rule bases illustrated above to perform the root cause analysis. In one aspect, any analysis technique can be used including neural networks, other rules bases, regressive learning, fuzzy logic, and other known diagnostic techniques or techniques yet to be discovered. With the examples

given here, there are a minimum of three process signals which are received, the control demand CD signal, the primary process variable PV signal and the setpoint SP signal. However, other process signals, fewer signals, or different signal combinations can be used to perform the root cause analysis.

Root cause analysis block 102 receives a model selection input 116 which is used to select one of the plurality of models 112. The model selection input can be from an operator or from another source. The model selection input 116 identifies one of the plurality of models 112 for subsequent use by root cause analysis block 102. Additionally, in one example, additional optional process (OP) signals can be selected for use with the selected model. If a graphical user interface is used, the models can include graphical models which can be displayed on a display output 118 and used in configuring the model. For example, the particular process signal can be assigned using the model selection input 116 to one of the process signals (PS_{1A}, PS_{1B} . . .) or optional process signals (OP_{1A}, OP_{1B} . . .) associated with a selected model. This assignment can be illustrated in a graphical form.

Once a model has been selected, the process signals used by the model rule base are assigned to the actual process signals received from the process. The root cause analysis block 102 can perform a root

cause analysis using any desired technique such as those set forth above. Based upon the root cause analysis, a root cause output 120 is provided which is an indication of the root cause of an aberration of an event which has occurred in the process.

Pursuant to one embodiment of the invention, Figure 5 is a simplified block diagram showing one physical implementation of process device 100. In the example of Figure 5, device 100 couples to a process control loop 132 through input/output 134. Loop 132 can be, for example, the two wire loop shown in Figure 1 or other process control loop. Further, the connection does not need to be a direct connection and can simply be a logical connection in which variables from the loop are received through a logical input/output block 134. A microprocessor 136 couples to a memory 138 and a graphical user interface 140. The memory 138 can be used to store variables and programming instructions, as well as models 112 shown in Figure 4.

The graphical user interface 140 provides an input for receiving the model selection input 116 as well as the display output 118 of Figure 4 for use during model selection and configuration. Microprocessor 136 can also couple to an optional database 142 which can contain information related to the configuration and operation of the process being monitored. For example, many process control or monitoring systems contain such databases. One

example is the AMS system available from Rosemount Inc. of Eden Prairie, Minnesota.

It is appreciated that the root cause process device 100 can be implemented in any process device such as transmitters, controllers, hand-held communicators, or the control room computer shown in Figure 1. In one embodiment, process device 100 will operate on a computer system or PC located in the control room or other remote location. Process control loop 132 will typically comprise some type of a Fieldbus based loop, or multiple control loops. In such a configuration, process device 100 can poll the desired process signals the various devices coupled to the control loop for the selected model. Although a graphical user interface 140 is shown, the model can be selected using any selection technique and does not need to be selected and configured by a human operator. For example, based upon configuration information stored in another location were provided through other techniques, the appropriate rule base and any model options can be received by device 100. Alternatively, the root cause process device 100 can be implemented in the field and reside in the transmitter for example.

As used herein, process variables are typically the primary variables which are being controlled in a process. As used herein, process variable means any variable which describes the condition of the process such as, for example, pressure, flow, temperature,

product level, pH, turbidity, vibration, position, motor current, any other characteristic of the process, etc. Control signal means any signal (other than a process variable) which is used to control the process.

5 For example, control signal means a desired process variable value (i.e. a setpoint) such as a desired temperature, pressure, flow, product level, pH or turbidity, etc., which is adjusted by a controller or used to control the process. Additionally, a control

10 signal means, calibration values, alarms, alarm conditions, the signal which is provided to a control element such as a valve position signal which is provided to a valve actuator, an energy level which is provided to a heating element, a solenoid on/off

15 signal, etc., or any other signal which relates to control of the process. A diagnostic signal as used herein includes information related to operation of devices and elements in the process control loop, but does not include process variables or control signals.

20 For example, diagnostic signals include valve stem position, applied torque or force, actuator pressure, pressure of a pressurized gas used to actuate a valve, electrical voltage, current, power, resistance, capacitance, inductance, device temperature, stiction,

25 friction, full on and off positions, travel, frequency, amplitude, spectrum and spectral components, stiffness, electric or magnetic field strength, duration, intensity, motion, electric motor back emf, motor current, loop related parameters (such as control loop

resistance, voltage, or current), or any other parameter which may be detected or measured in the system. Furthermore, process signal means any signal which is related to the process or element in the process such as, for example, a process variable, a control signal or a diagnostic signal. Process devices include any device which forms part of or couples to a process control loop and is used in the control or monitoring of a process.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention. Although two example processes and example models are shown in this description, the invention is applicable to other process configurations and models can be generated using known techniques or techniques discovered in the future. Further, other types of rule bases or model configurations can be used with the present invention. The invention can be implemented in a stand alone device or can be a software module which is added to software used to control or monitor industrial processes. In one aspect, the invention includes the computer instructions and/or storage media used to implement the invention. As used herein, a "process model" is any logical representation of a process and is not limited to the specific examples set forth herein. A

"root cause" is the initial cause (or causes) of a variation or aberration in process operation. Other types of process control loops which can be modeled include, but are not limited to, flow control, level control, temperature control, etc., including regulator control and cascade control of gases, liquids, solids or other forms of process material. Specific examples of loops include a flow control loop with valve driven by differential pressure, a level control loop with valve driven by differential pressure, temperature regulatory control to flow regulatory control, level regulatory control to valve pump driven, flow control with valve driven by pump, level regulatory control to valve chiller condenser, level regulatory control to flow regulatory control cascade feed, liquid temperature regulatory control to valve, liquid temperature regulatory control to flow regulatory control, gas flow control with valve driven by differential pressure, gas temperature regulatory control to valve, gas pressure regulatory control to valve, gas pressure regulatory control to flow regulatory control, level regulatory control to flow regulatory control cascade reboiler, liquid pressure regulatory control to valve and level regulatory control to valve reboiler, for example. Various types of process elements which can be controlled include drums and tanks, heat exchangers, towers, steam systems, condensers, boilers, reactors,

and heaters, compressors, fuel systems, turbines and
flare systems, for example.

5